12

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Progress is reviewed for a research program which has examined the multi-axial deformation and fracture behavior of Ti alloys, particularly as influenced by impurities such as hydrogen and by microstructural defects such as porosity. The studies range from experimental and analytical modeling of critical fracture processes to structure-property studies of both wrought material in the form of sheet and powder fabricated material in bar form. Specifically the program has studied:

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1) the modeling of ductile fracture through an examination of the deformation and fracture at isolated holes in plane-strain tension;

2) the deformation and fracture of P/M Ti and Ti-6Al-4V containing porosity;

3) the influence of hydrogen on the multiaxial deformation and fracture behavior of beta-phase(bcc) Ti-30V and alpha(hcp)-beta Ti-6Al-4V,

4) the theory of localized necking of sheet at negative minor strains.

Introduction

The in-service operation of Ti alloy components usually depends critically on their deformation and fracture properties under multiaxial operating states of stress. Furthermore, these alloys often contain impurities such as hydrogen in sufficient quartities to degrade their behavior. Thus, understanding the deformation and fracture behavior under multiaxial state of stress (as well as the effect of hydrogen thereon) becomes essential not only for improving these properties by heat treatment or processing techniques but also for the fail safe utilization of Ti alloys. In addition, the high cost of a finished part has become an important limitation to the more extensive usage of Ti alloys. As most of the cost of a wrought Ti alloy component is often associated with the large amount of starting material to produce a structural part,[1,2] there has been a major thrust to explore the processing of Ti alloy parts to near-net shape. Thus, powder metallurgy (P/M) has emerged as an attractive alternate route for processing Ti alloy components. The problem is that powder fabrication of Ti alloys results in materials whose properties, especially ductility and fatigue resistance, are often inferior to their conventionally cast and wrought counterparts. This is usually due to the presence of porosity and/or inclusions,[1-7] which occur in P/M alloys but are not present in wrought Ti alloys.

The present research program seeks to provide a broad-based understanding of the multiaxial deformation and fracture behavior of Ti alloys, particularly as influenced by impurities such as hydrogen and by microstructural defects such as porosity. The studies range from experimental and analytical modeling of critical fracture processes to structure-property studies of both wrought material in the form of sheet and P/M material in bar form. Substantial progress has been achieved in these studies during the period Oct. 1, 1981 to Sept. 30, 1982 in the following areas:

1) the modeling of ductile fracture through the study of deformation and fracture at isolated holes in plane-strain tension,

2) the deformation and fracture of P/M Ti and Ti-6Al-4V containing porosity,

3) the influence of hydrogen on the multiaxial deformation and fracture behavior of beta-phase (bcc) Ti-30V and alpha (hcp)-beta Ti-6Al-4V,

4) the theory of localized necking of sheet at negative minor strains.

A significant aspect of this program is the educational experience which it provides to the graduate students involved. In the past fiscal year the program has supported: Charles Lentz, M.S., Nov., 1981, (currently at Western Electric Co., Reading PA); Roy Bourcier, Ph.D. candidate; Barbara Lograsso, who has just completed the M.S.; and two new graduate students, Paul Magnuson and Dale Gerard.

Deformation and Fracture at Isolated Holes in Plane-Strain Tension
(with Roy Bourcier, Ph.D. candidate, R. E. Smelser, W. Spitzig, and O. Richmond, Research Laboratory, U.S. Steel Corp.)

Ductile fracture in high-strength alloys is a result of the termination of stable plastic flow by catastrophic strain localization. Microstructurally, this flow localization can often be traced to the presence of large voids or pores within the material. These voids may be formed at large inclusions during straining or may already exist as porosity in a powder metallurgy product or a casting. In a unique initial attempt to model the ductile fracture of material containing pre-existing voids or pores, the deformation and fracture of single-hole plane-strain tension specimens has been examined experimentally and analyzed by a large strain elastoplastic finite-element model.[8-10]

The study is based on the contrasting behavior of two materials, one with a relatively high strain hardening rate (an HSLA steel), and the other with a low rate (Ti-6Al-4V). Deformation around the hole, associated necking of the ligaments, as well as the overall force-elongation response exhibits excellent agreement with predictions from a large-strain elastoplastic finite-element model (FEM). Figure 1 is an example of the good agreement between the FEM and experiment. An important result of this study is that failure of the high strain-hardening material occurs by ductile tearing across the ligaments whereas failure of the low-hardening material occurs by shear localization. This behavior, shown in Figure 2, illustrates the influence of work hardening on the development of plastic flow in the presence of a geometric inhomogeneity. In the Ti-6Al-4V material (Figure 2a), the low rate of work hardening leaves the material with relatively little resistance to the rapid development of inclined bands of intense deformation from the hole surface outward to the specimen face. At a critical level of extension this ligament becomes plastically unstable, and fracture proceeds by shear localization and ductile rupture. In the HSLA steel (Figure 2b), the high rate of work hardening allows deformation to be diffused over most of the ligament and retards the development of the band of shear localization. As a result, considerable hole growth occurs and much tensile elongation occurs within the ligament. This alters the geometry of the hole such that its ability to cause an inclined band of intense deformation is retarded, and the strain localizes across the minimum-width section of the ligaments instead. As a result, fracture occurs by tensile rupture across the minimum-width section, normal to the tensile axis, as in Fig. 2b. The strains within the inclined deformation band induced by the specimen geometry simply do not attain the level necessary to induce a shear instability when the strain hardening rate of the material is high*.

We believe that the processes seen here should be analogous to those operative in the fracture of materials containing voids/porosity. Although the detailed nature of the deformation zones induced by a random array of voids/pores will be different than in our simple model, the principal effect

*One advantage of the FEM analysis is the ability to model flow behavior beyond the experimental fracture strain. This has the important advantage of illustrating deformation patterns which would develop if fracture did not first intervene.

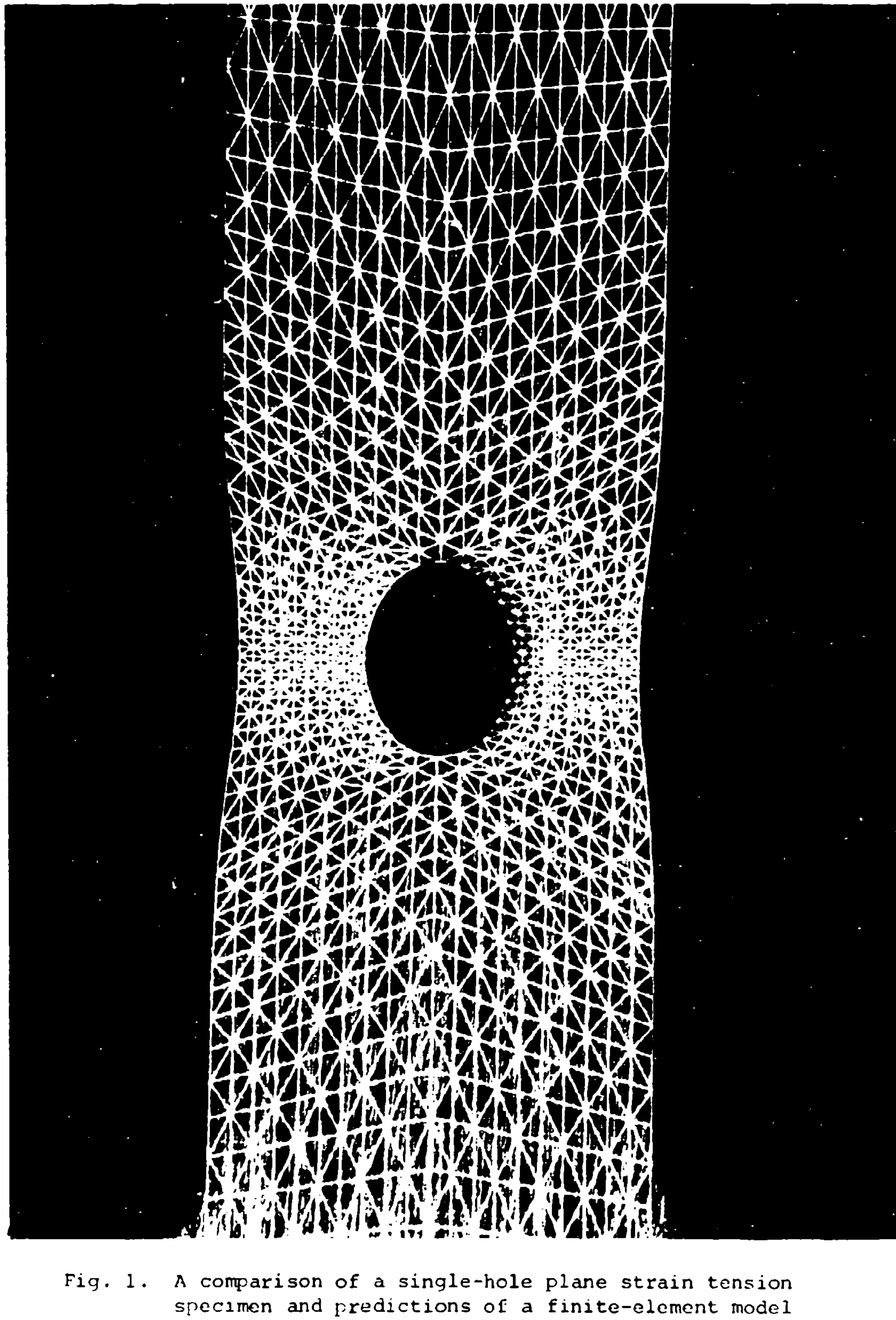

Fig. 1. A comparison of a single-hole plane strain tension specimen and predictions of a finite-element model at an equivalent extent of axial hole grc·th. The material is the HSLA steel USS EX-TEN F50 Mod.

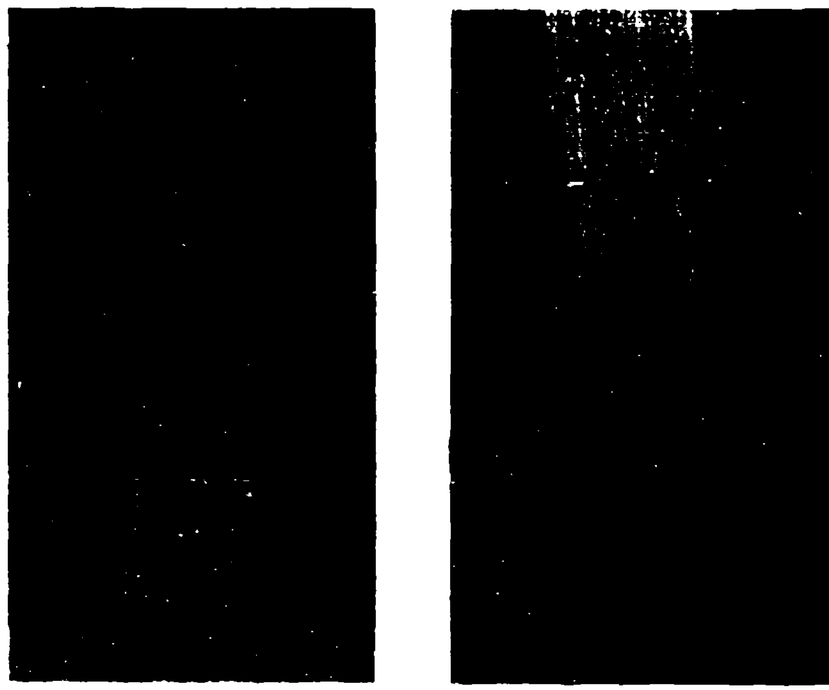

Fig. 2. Profiles of fractured single-hole plane strain specimens: (a) Ti-6Al-4V and (b) the HSLA steel EX-TEN F50 Mod.

will still be one of geometrically-induced flow localization. The ability of the matrix material to distribute strain within the ligaments between voids/pores is critical in determining the rate at which this localization proceeds. For a given void population, increased work hardening will delay the onset of instability. As a result of the delay, considerable tensile deformation within the ligament occurs. The resulting hole growth tends to localize strain in the minimum-width section of ligaments normal to tensile axis. Given the presence of second phase particles which may debond or fracture at low strains, the ligaments will thus fail by a ductile, tearing mode normal to the tensile axis in materials with a high rate of work hardening. In contrast, a material with a low strain hardening rate is not able to diffuse slip effectively, and the presence of a void acts to induce an inclined band of localized deformation [a shear instability]. Thus a failure mode transition, which is sensitive to work hardening, is a natural consequence.

In summary, this study indicates the importance of work hardening in determining whether failure occurs by: (1) a shear instability process [and a small strain to failure] when the strain hardening rate is low [as in the Ti-6Al-4V] or (2) a tensile rupture process which is associated with hole growth and a high rate of work hardening [the HSLA steel] and which is associated with failure at larger strains.

Deformation and Fracture of P/M Ti and Ti-6Al-4V Containing Porosity
(with Roy Bourcier, Ph.D. candidate)

The degradation of mechanical properties, notably tensile ductility and fatigue crack initiation behavior, of P/M Ti-6Al-4V produced by the elemental approach is well known. While previous studies clearly relate the observed loss of properties to the residual porosity present[1-7], the failure mechanism(s) are not understood. The purpose of this research is to establish in a fundamental manner the influence of porosity on the ductile fracture behavior of P/M Ti alloys containing porosity.

Assuming the work hardening and the level of porosity to be the controlling material parameters, the study is based on the contrasting behavior of (commercially pure) CP Ti ($n = d\ell n\sigma/d\ell n\sigma \simeq 0.17$) and Ti-6Al-4V ($n \simeq 0.06$) which contain spherical isolated porosity at levels of ~93, 96 and 99% of the theoretical density and which will be compared to fully dense specimens. Considerable effort thus far has been devoted to fabricating P/M specimens. With the assistance of Imperial Clevite (formerly Gould Materials Laboraboratory), Ti-6Al-4V has been powder fabricated in the following forms: (a) the "standard" Clevite material at 99% density (Ti sponge "fines" with high chloride content processed using the proprietary "MR-9" process); (b) Widmanstatten material also at 99% density (Teledyne Wah-Chang, hydride-dehydride Ti powder, low chloride content, MR-9 processing); and (c) Widmanstatten material, same as (b) except conventional processing to ~97% density (see Figure 3a). At MTU we have processed the hydride-dehydride CP Ti powder using: (a) cold die pressing at 100 ksi (689 MPa) and sintering at 1325°C/4 hrs. to ~96% density, see Figure 3b, and (b) cold isostatic pressing at 40 ksi and sintering at 1325°C/4 hrs. to ~93% density.

A laboratory scale, hot isostatic press (HIP) unit (ASEA Pressure Systems) capable of 30,000 psi (207 MPa) at 1500°C has very recently been installed at MTU and is now operational. The press is the first HIP unit to be installed at any university the the U.S. As such, it extends our P/M processing capability such that, for example, the microstructures in Figure 3 can be HIP'd to~100% density.

To date, only preliminary tensile testing has been performed but it does indicate an important limitation to these materials. The tensile ductility of individual specimens of 99% Ti-6Al-4V (hydride-dehydride starting Ti pow-

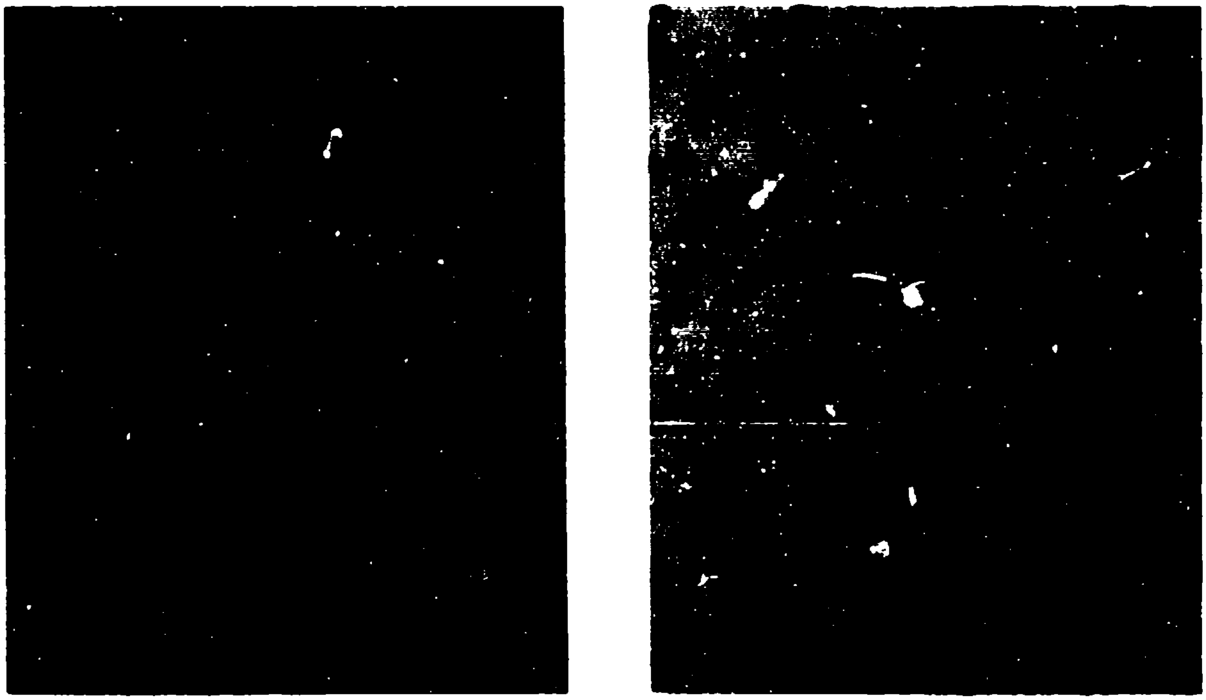

Fig. 3. Optical micrographs showing cold pressed and sintered: (a) Ti-6Al-4V at 97% density and (b) CP Ti at 95% density. Note the rounded, isolated porosity. 100X

As proper design standards usually assume minimum properties, the specimen to specimen variability in ductility obviously imposes a significant limitation on the utilization of this P/M material.

The Influence of Hydrogen on the Multiaxial Deformation and Fracture Behavior of Beta-Ti-30V and Alpha-Beta Ti-6Al-4V Sheet
(with Barbara K. Lograsso, M.S., Oct., 1982)

Studies previously performed as part of this program have shown that commercially pure (α-phase) Ti sheet exhibits a dramatic loss of ductility due to internal hydrogen under balanced biaxial deformation even though no loss of ductility is detected in uniaxial tension.[11] This dependence of hydrogen embrittlement on multiaxial loading path is a result of void formation due to fractured hydrides and subsequent dependence of void growth and coalescence on the multiaxial deformation path.[12] However, α-β Ti alloys do not readily exhibit hydrogen embrittlement except at very high hydrogen contents or in the presence of locally high triaxial stresses caused by cracks or notches. This behavior may be interpreted to result from the high solubility of hydrogen in the bcc β-phase which acts as a sink for the hydrogen in α-β Ti alloys. Thus the role of the crack or notch is to provide the local triaxial stress state which acts to accumulate hydrogen to the level necessary for hydride formation.[13,14] The following question remains: will an α-β or β-phase Ti alloy be susceptible to hydrogen embrittlement under uniform multiaxial loading (no cracks or notches) if the hydrogen remains in solution (hydrides do not form)?

The purpose of this study has been to examine the influence of hydrogen on the deformation and fracture behavior of β-phase Ti-30V and α-β Ti-6Al-4V alloy sheet under multiaxial states of stress. Uniaxial tensile and punch-stretch tests have been utilized to examine Ti-30V containing 40 or 2000 wt. ppm H as well as Ti-6Al-4V with either 30, 250, or 500 wt. ppm H.

The behavior of Ti-30V in uniaxial tension at room temperature indicates that at levels of 2000 wt. ppm, H has no effect on the strength, but causes a small increase in strain rate hardening and a small decrease in strain hardening. The net effect is that no significant change in either the localized necking or fracture behavior for any loading path between uniaxial tension and balanced biaxial stretching. Fig. 4 shows this behavior in terms of forming limit and fracture limit diagrams for the bcc Ti-30V alloy.

Similarly the uniaxial tensile behavior of the Ti-6Al-4V indicates that H (at least up to 500 wt. ppm) has no significant effect on the following: yield stress, strain rate hardening exponent, strain hardening exponent, and plastic anisotropy. In addition, the fracture limit diagram for the Ti-6Al-4V sheet indicates that (like Ti-30V) there is no significant influence of hydrogen on the fracture behavior over a range of stress states from uniaxial tension to balanced biaxial tension for the equiaxed α/β microstructure examined.

Previous results on pure Ti have shown a marked susceptibility to hydrogen embrittlement in equibiaxial tension even though no effect was observed in uniaxial tension.[11] In the present study the surprising result is that even in a test as severe as equibiaxial tension, both the Ti-30V and Ti-6Al-4V sheet remain immune to hydrogen embrittlement even at high levels of hydrogen in solution, up to ~9 at. % in the case of the β-phase alloy! Such behavior may be understood if one accepts that hydrogen, unlike other interstitial atoms, dilates the bcc lattice of the β-phase in an isotropic manner such that no tetragonal component exists in the stress field near the H atom.[15,16]

We thus conclude that H is not likely to cause hydrogen embrittlement in any Ti alloy if hydrides do not form and provided that phase stability is retained.[15,17,18] Given that the β-phase appears to act as a relatively innocous sink for H, the resistance to hydrogen embrittlement of an α-phase alloy such as CP Ti can be substantially improved by adding a small amount

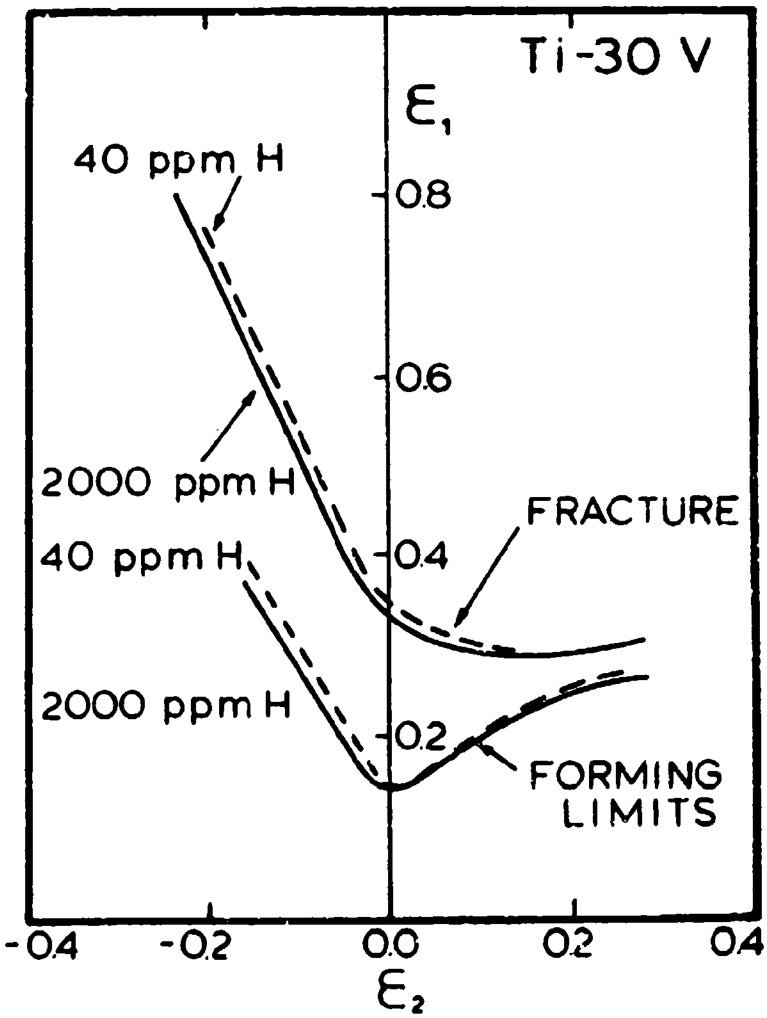

Fig. 4. A comparison of the forming limit strains for the onset of localized necking and the fracture strains for Ti-30V sheet at 40 and 2000 ppm H. The strains ε_1 and ε_2 are the major and minor principal strains in the plane of the sheet.

of an element which stabilizes the β-phase and causes formation of at least a small volume fraction of the β-phase upon heat treatment.

Localized Necking of Sheet at Negative Minor Strains
(with K. S. Chan, Southwest Research Institute and A. K. Ghosh, Rockwell International Science Center).

The ductility of sheet is usually limited by the onset of localized necking in which deformation concentrates into a narrow bond or trough of material. Thus localized necking limits the usable ductility in most stretch forming operations, and it is important to understand such behavior in order to improve not only sheet metal formability but also ductility of sheet in general. In this study, localized necking in sheet metal has been examined for strain paths between uniaxial tension and plane strain (i.e., the negative minor strain region of a forming limit diagram). The behavior of sheet with pre-existing imperfections has been analyzed and is contrasted to that free of imperfections. In particular, it is shown that the size and orientation of an imperfection is critical in determining whether or not localized necking is initiated along the imperfection. The influence of strain hardening, strain rate hardening, and plastic anisotropy on localized necking of an imperfect sheet is also examined. One of the most significant conclusions obtained from present analysis and from a re-examination of Hill's theory[19] is the prediction of a critical thickness strain criterion for the onset of localized necking at negative minor strains, regardless of whether or not an imperfection is present. As shown in Fig. 5, the critical thickness strain criterion is observed in Ti alloys, Al alloys, steels and brass.

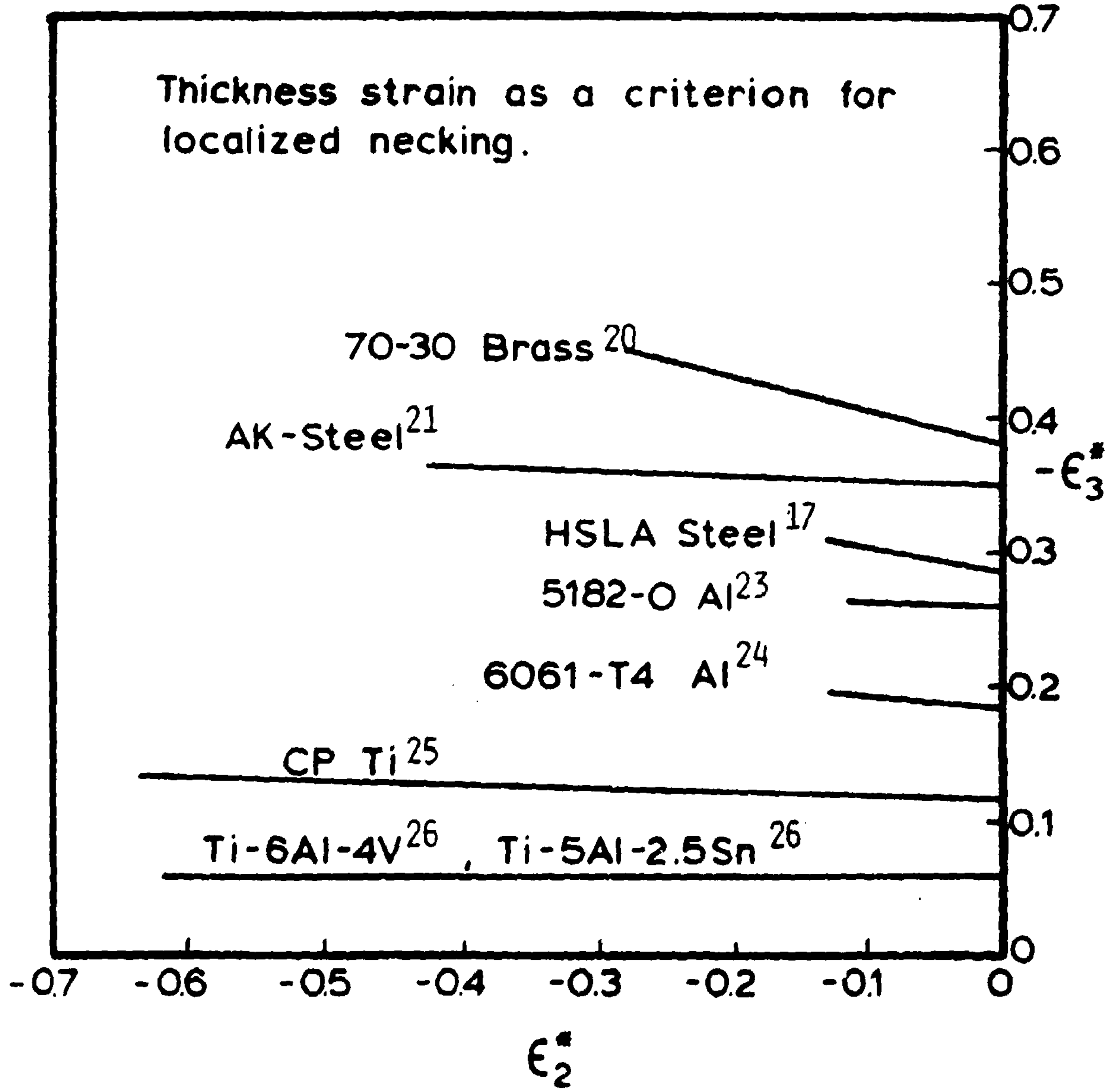

Fig. 5. An illustration of the onset of localized necking in sheet occurring at a critical thickness strain in the negative minor strain region of the forming limit diagram.

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